The Charm Renaissance: D-physics – a Selective Review

- Charm physics: why we live in interesting times
- Experimental facilities and techniques
- Charm and precision CKM physics
- Searches for new physics in charm decays
- Conclusions

Guy Wilkinson (University of Oxford)
On behalf of the CLEO-c collaboration

Charm physics: extinct, dormant or active ?

A common view:

“Charm physics: illustrious past which played essential role in foundation of Standard Model, but not much present & still less future. B physics is where it’s all at.”

Some reasons that charm may appear underwhelming:

- Slow oscillation rate;
- Very low level of CP violation;
- Interesting physics masked by long distance dynamics.

Is this fair, or does charm remain a very important research, area, indeed one where new interest is erupting right now?

A Sporting Analogy

The future is bright (cf. b physics)…

English and European champions

Yesterday’s men (cf. c physics):

18 times league championships –
but none for 18 years (and counting)

Charm physics – a new dawn

There are several good reasons why charm physics is back in the limelight:

1) Precision CKM tests

Success of the B-factories and the Tevatron has meant that unitarity triangle tests are entering a new, precision era. Although the CKM elements being studied are those accessible in B-decays, charm turns out to be a vital ingredient in programme.

2) Charm mixing and its legacy

Discovery of D^0-$\bar{D}^0$ oscillation was HEP highlight of last 2 years. Higher than expected rate is (arguably) intriguing in its own right, and points the way forward to searches for CPV.

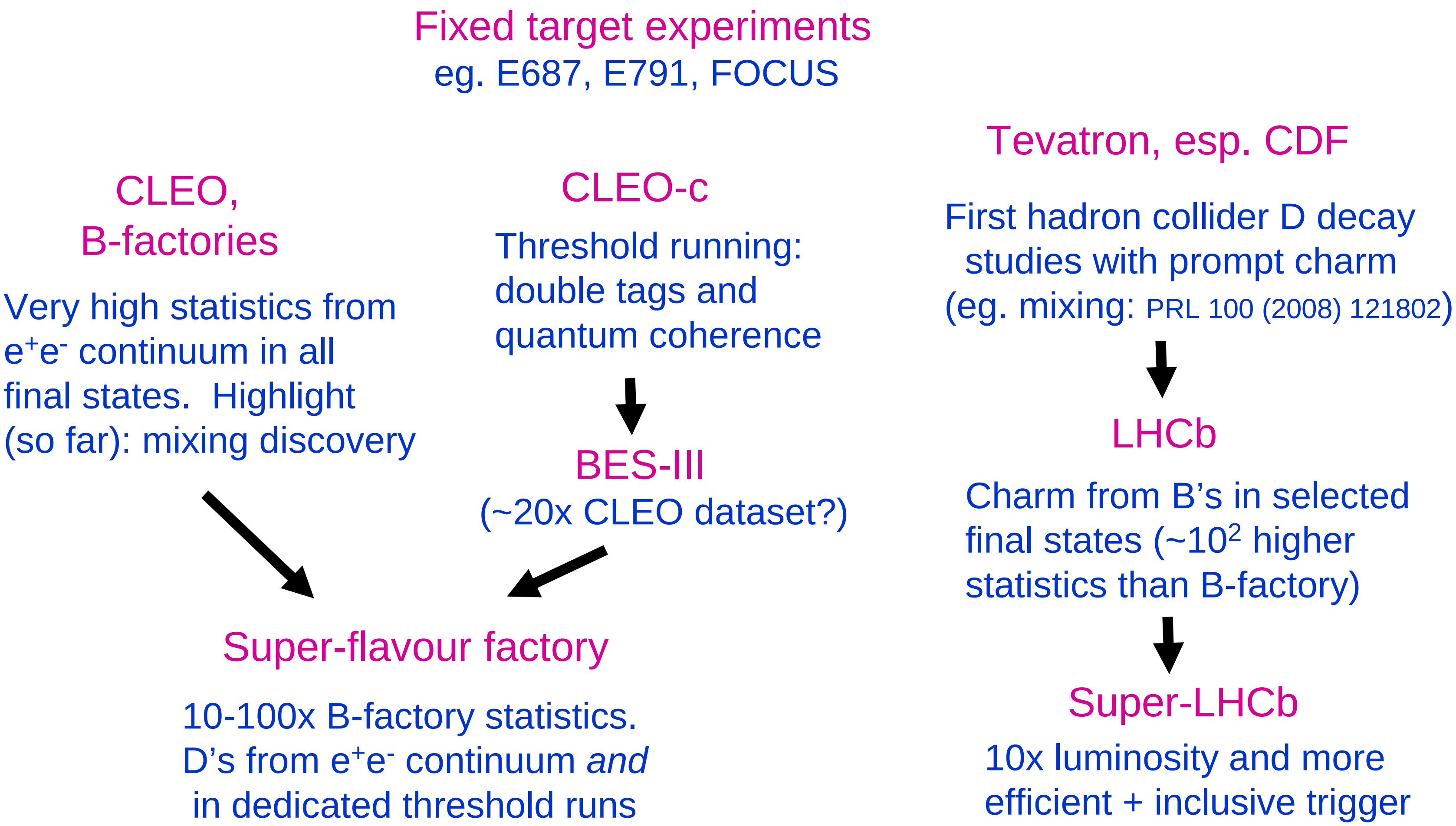
3) Recent discoveries in spectroscopy

Discovery of narrow c-$\bar{c}$ states above threshold (X,Y,Z) and narrow excited D_s states. (But not discussed further today.)

Charm physics certain to have an exciting few years ahead (unlike Liverpool FC)

Facilities, experimental attributes and Dalitz plots

Charm Facilities – Recent Past, Present & Future



Fixed target experiments
eg. E687, E791, FOCUS

CLEO,
B-factories

Very high statistics from e^+e^- continuum in all final states. Highlight (so far): mixing discovery

CLEO-c

Threshold running: double tags and quantum coherence

BES-III
(~20x CLEO dataset?)

Super-flavour factory

10-100x B-factory statistics. D's from e^+e^- continuum *and* in dedicated threshold runs

Tevatron, esp. CDF

First hadron collider D decay studies with prompt charm (eg. mixing: PRL 100 (2008) 121802)

LHCb

Charm from B's in selected final states (~10^2 higher statistics than B-factory)

Super-LHCb

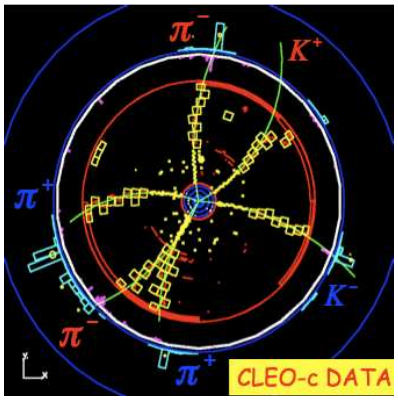
10x luminosity and more efficient + inclusive trigger

Charm Studies at Threshold (CLEO-c)

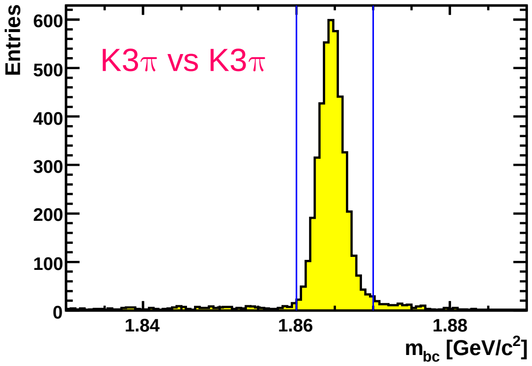
CLEO-c accumulated 818 pb^{-1} at $\psi(3770)$ and 586 pb^{-1} at 4170 MeV (for D_s production)

Some advantages of threshold running:

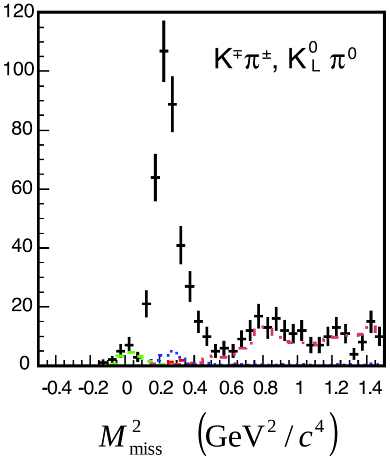
- Very clean – no fragmentation particles. Double tag studies have v. low bckgds



$\psi(3770) \rightarrow D^+(K^-\pi^+\pi^+)D^-(K^+\pi^-\pi^-)$



- Unseen particle reconstruction through kinematic constraints, eg. K^0_L and ν.



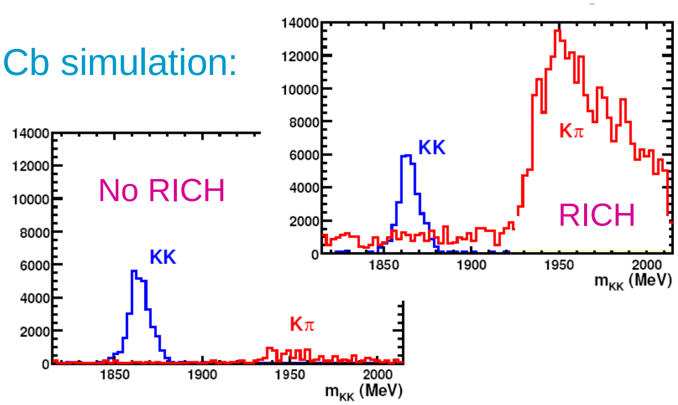
- Quantum coherence. ψ (3770) gives C=-1 state → CP-tagging possible !

Necessary Experimental Attributes

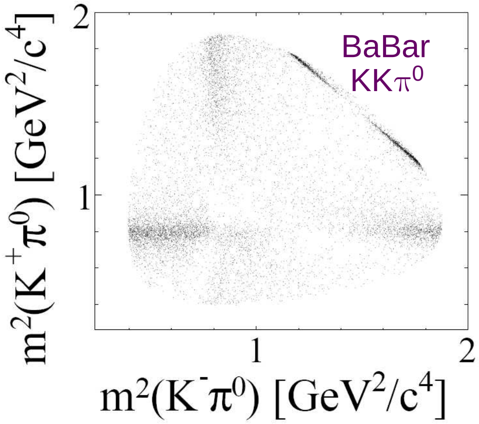
Characteristics needed for successful D physics ~ those required for B physics

- Efficient tracking and (if possible) good calorimetery for γ and π^0 reconstruction
- Hadron identification abilities

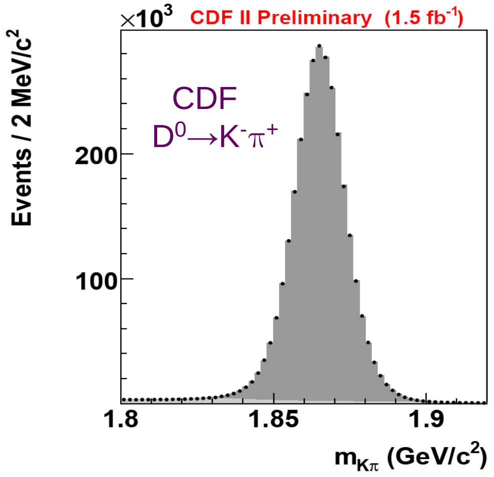
LHCb simulation:



- In hadronic environment need trigger system sensitive to final states of interest



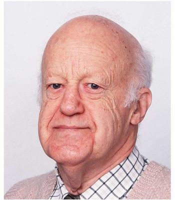
PRD 76 (2007) 011102 (R)



PRL 100 (2008) 121802

Experimental Techniques: Dalitz Plots

Dalitz plot is invaluable technique exploited in many charm analyses.



Richard Dalitz
1925-2006

Kinematics of 3-body decay D→A,B,C fully described by 2 parameters. Typical choice:

$$m^2_{AB} \equiv (p_A + p_B)^2 \; ; \; m^2_{BC} \equiv (p_B + p_C)^2$$

Lorentz invariant, and phase space flat. Allows resonances to be clearly seen.

Charm Dalitz plots have many uses:

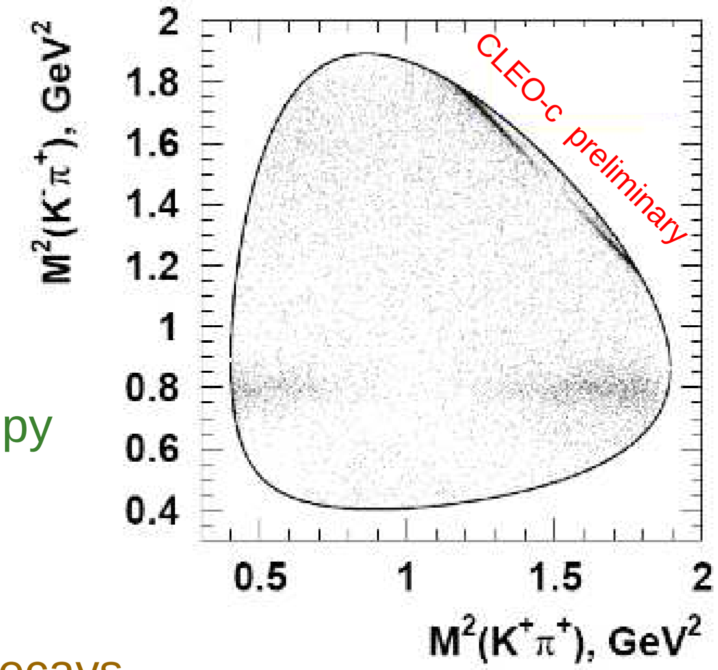
1) as a probe of light meson spectroscopy

2) key role in the CKM-γ measurement

3) mixing and CPV studies

Can be extended to 4- (and more) body decays

$D^+ \to K^+K^- \pi^+$



Dalitz Plots and Resonance Models

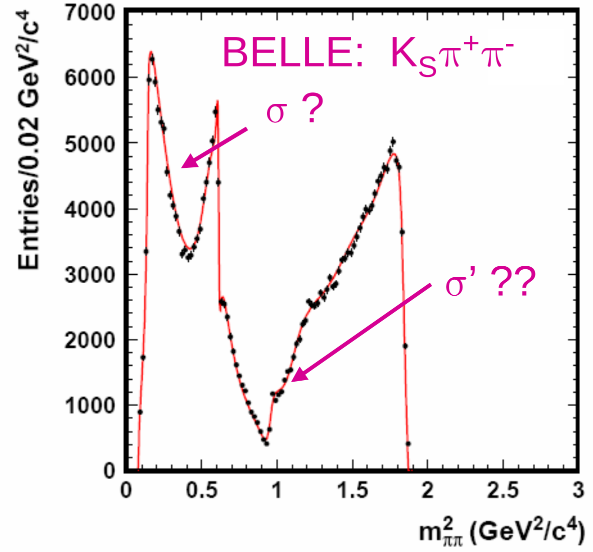
To extract physics contributing to a Dalitz plot, necessary to develop a model

Common choice: isobar model - fit a_j, b, α_j, β:

Non-resonant term

$$A(m_{12}^2, m_{13}^2) = \Big[\sum_j a_j\, e^{i\alpha_j} A_j(m_{12}^2, m_{13}^2)\Big] + b e^{i\beta}$$

Sum over resonances



where amplitudes described as follows:

$$A_j(m_{12}^2, m_{13}^2) = F_D^J\, F_D^r\,.\, M_r^j\,.\, BW_r^j$$

Blatt-Weisskopf form factors (angular momentum barrier penetration)

Relativistic Breit-Wigner

Angular distribution

Works well for P-, D-wave, but not so well for S-wave.

Not great for broad overlapping resonances, eg. σ,σ' ?,κ ? (& unitarity violated).

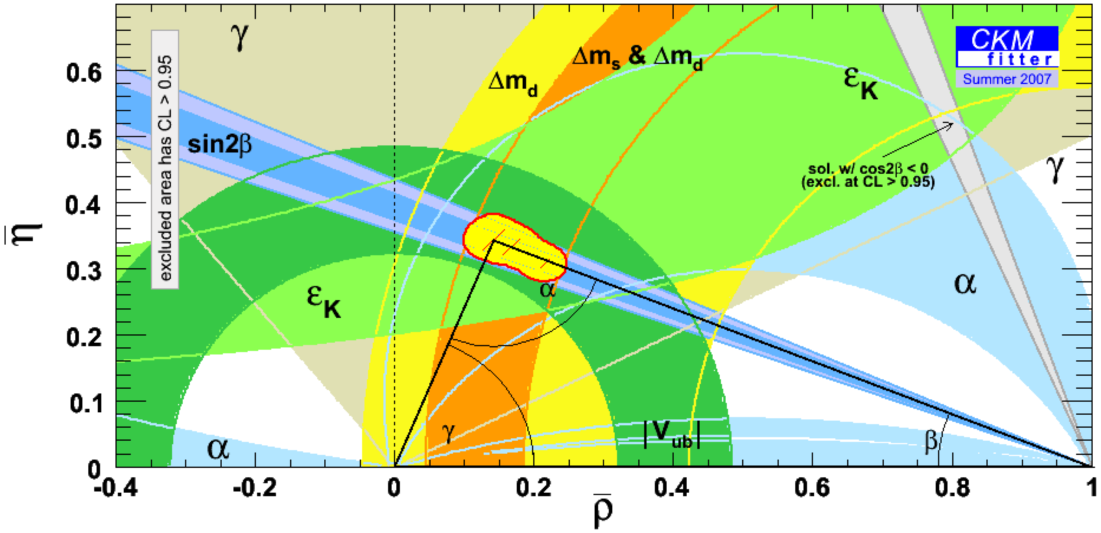
Here alternative treatments preferred based on scattering data, eg. LASS for Kπ (Aston et al. Nucl. Phys. B 296 (1988) 493), and K-matrix for ππ (I.J.R.Aitchison, Nucl. Phys. A189 (1972) 417)

D decays and the CKM unitarity triangle

- Measurements of γ with B→DK
- Lattice QCD tests and the 'mixing side'
- (Not covered: semileptonic decay rates and form factors, branching ratio measurements etc)

The Unitarity Triangle and D decays

Classical unitarity triangle is constrained by quantities measured in B decays



But *key* measurements have high dependence (direct & indirect) on D decays:

- Tree-level measurements of angle γ

  At present $\gamma^{measured} = 77 \pm 31^{o}$

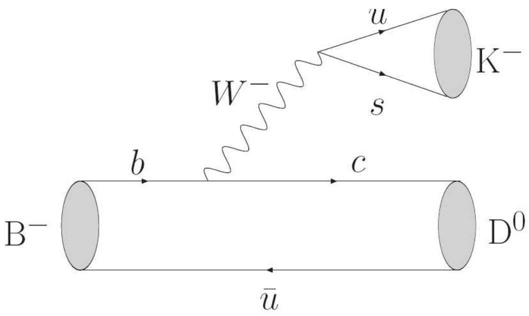
- Lattice QCD input to side opposite to γ

  This side and sin2β gives $\gamma^{predicted} = 68 \pm 4^{o}$

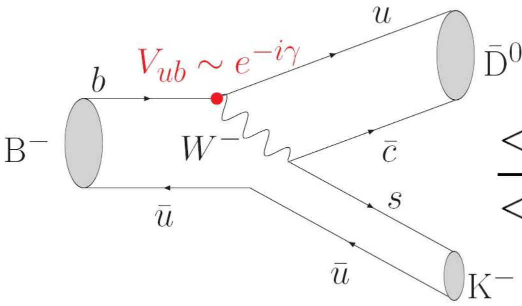
Improve this,
verify that,
and compare…

γ from $B^{\pm} \rightarrow DK^{\pm}$

$B^- \longrightarrow D^0 K^-$



$B^- \longrightarrow \overline{D}^0 K^-$



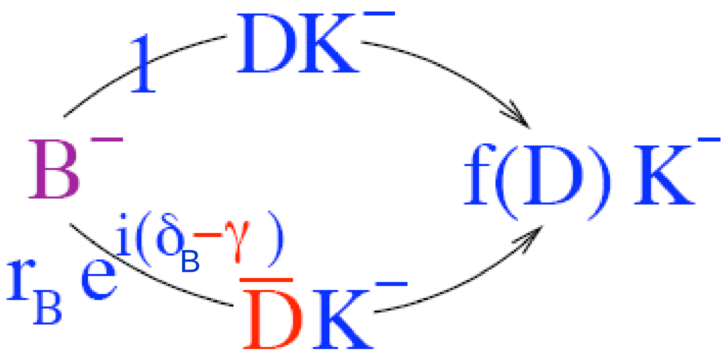
Colour/CKM suppressed – r_B~0.1

$$\frac{< B^- \longrightarrow \overline{D}^0 K^- >}{< B^- \longrightarrow D^0 K^- >} = r_B e^{i(\delta_B - \gamma)}$$

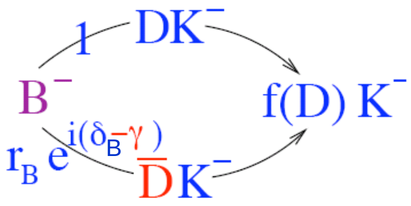
- Extraction through interference between b→u and b→c transitions
- Require D^0 and $\overline{D}^0$ decay to a common final state, f(D). Today consider 2 possibilities:

  $K^0_S\pi\pi$; $K\pi$; ($K\pi\pi\pi$ - see backups)

- Tree level processes: little sensitivity to New Physics → SM 'standard candle'



Dalitz Plots for γ at Belle & BaBar

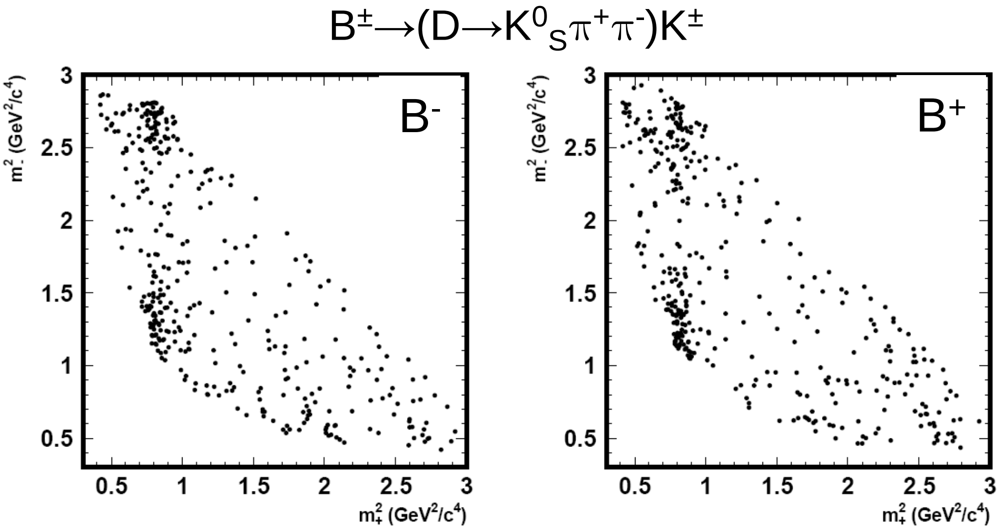


A powerful (and at *present*, only statistically useful) choice of common state f(D) is $K_s\pi^+\pi^-$. Rich resonant substructure.

Differences between B^- and B^+ Dalitz plots allow γ to be extracted in unbinned fit…

…need to understand different amplitudes from D^0 and $\bar{D}^0$ decay across Dalitz space, esp. variation in strong phase

Need a D decay model !


$B^\pm \to (D \to K^0_S \pi^+ \pi^-) K^\pm$

BELLE: arXiv:0803.3375

BaBar (383M BB) $\gamma = 76^\circ \pm 22^\circ(\text{stat}) \pm 5^\circ(\text{sys}) \pm 5^\circ(\text{model})$ r_B=0.09±0.09

BELLE (657M BB) $\gamma = 76^{\circ}{}^{+12^\circ}_{-13^\circ}(\text{stat}) \pm 4^\circ(\text{sys}) \pm 9^\circ(\text{model})$ r_B=0.16±0.04

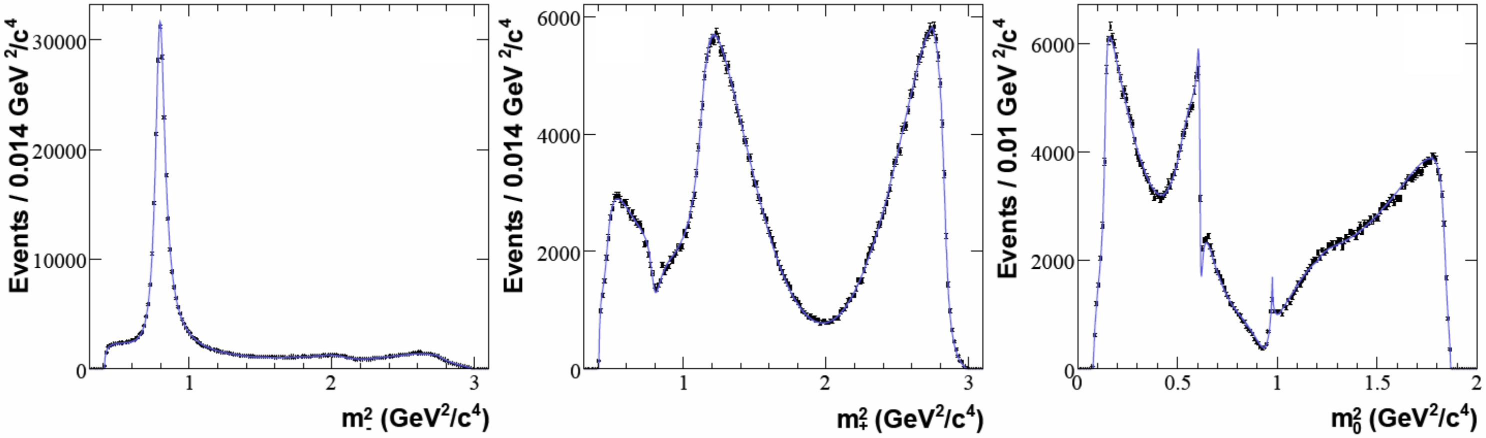
LHCb with 10 fb^{-1} can approach 3^o statistical error

(NB sensitivity scales with r_B.
All B→DK data suggest ~0.10)

Modelling the $K_s\pi^+\pi^-$ decay

Unbinned fit of Dalitz space in $B\rightarrow D(K_s\pi^+\pi^-)K$ decays requires reliable model of D decay. Model developed on flavour tagged D* decays.

State of the art – BaBar model fitted from 487k decays:



arXiv:0804.2089

Ingredients – 10 resonances described with isobar model. S-wave ππ and Kπ treated with K-matrix approach and LASS parametrisation respectively

(χ^2 / ndf = 1.11 to be compared with 1.20 for pure isobar model)

Impressive work – error on γ estimated to be 5°. But model systematic, even this small, uncomfortable for future very high stats measurements eg. LHCb.

CP- tagged Dalitz Plots

Dalitz plots of CP-tagged decays at the Ψ'' provide orthogonal info to flavour tagged events accessible in, eg., D* decays. They access the strong phase difference between the D^0 & $\bar{D}^0$ – vital information in the γ measurement

$D^{*+} \to D^0 \pi^+$

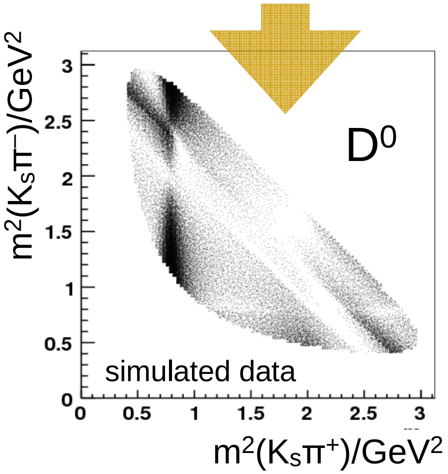
$D^0 \to K_S\pi^+\pi^-$

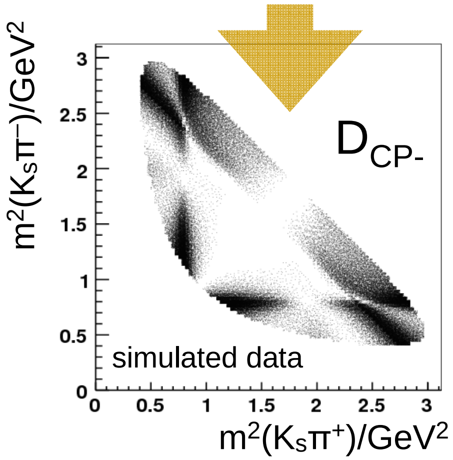
$\psi'' \to D_a D_b$

$D_a \to KK$ eg. CP+

$D_b \to K_S\pi^+\pi^-$

Flavour tagged distribution ∝ $|D^0|^2$ or $|\bar{D}^0|^2$





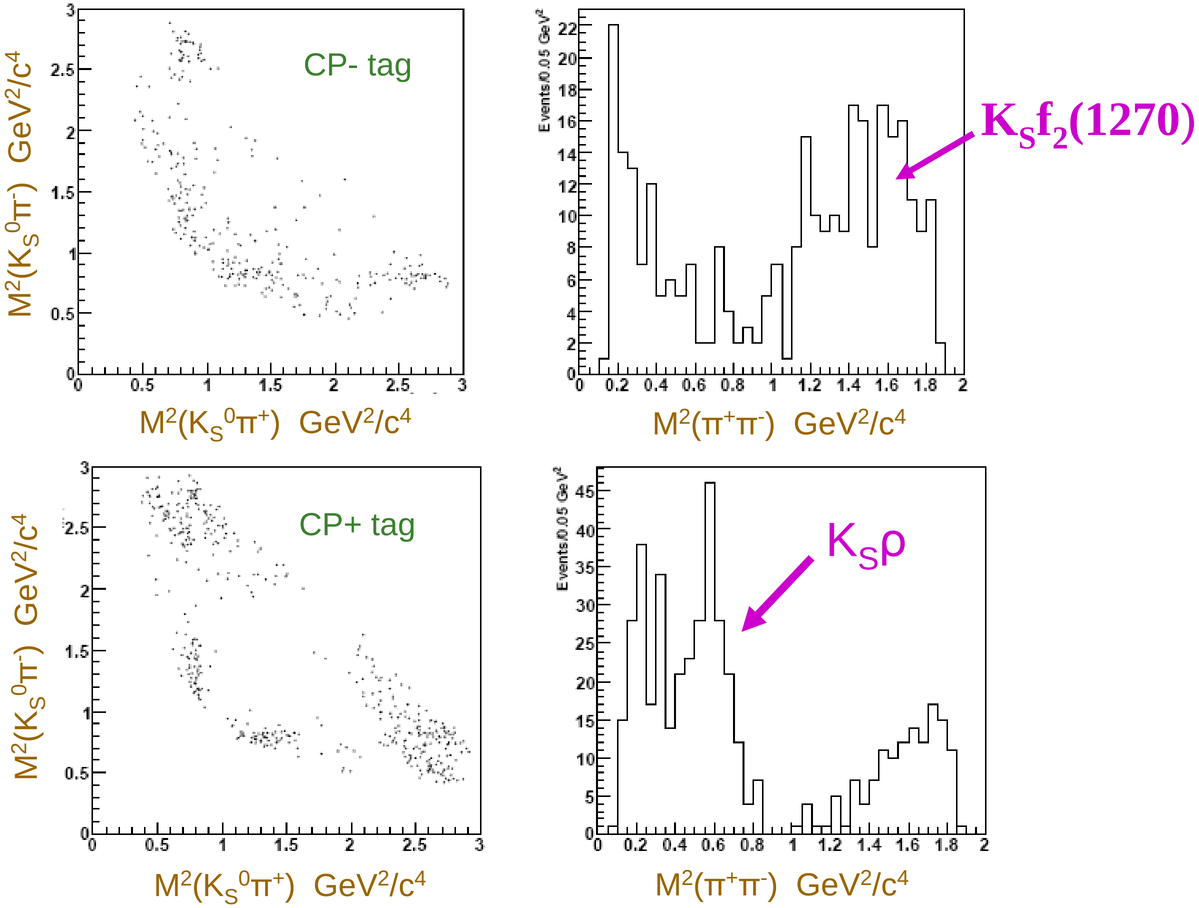
CP-tagged ∝ $|D^0|^2 + |\bar{D}^0|^2 \pm 2 D^0\bar{D}^0 \cos\delta$

With both flavour and CP-tagged data we may either validate model, or avoid model *entirely* and used measured quantities as input to binned fit !

CP-tagged $K_s\pi^+\pi^-$ Dalitz plots

Clear differences seen between CP-odd and CP-even:

CLEO-c preliminary,
~800 CP-tagged $K_s\pi^+\pi^-$



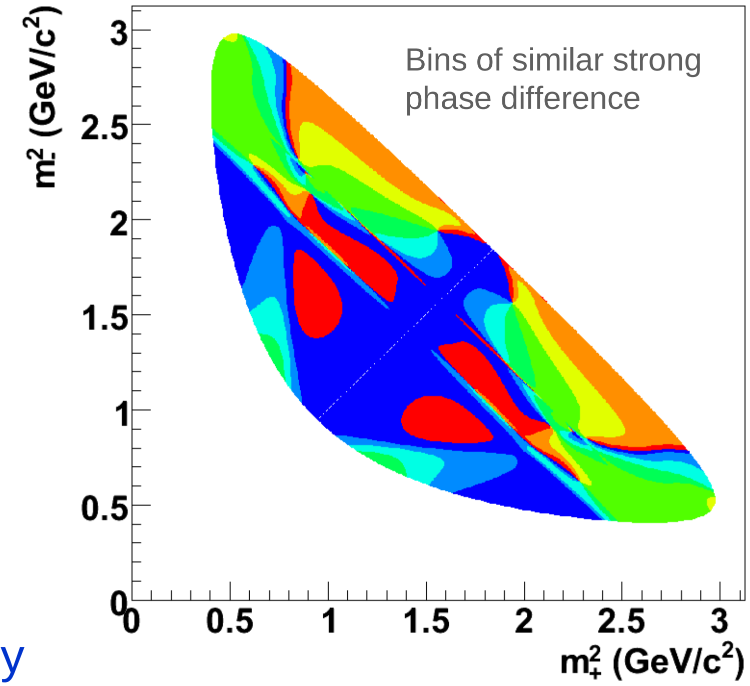
Binned Analysis of $B^{\pm} \rightarrow D(K_s\pi^+\pi^-)K^{\pm}$

CP-tagged data can be used to avoid entirely need for model.

Expected number of events in bins of Dalitz space can be expressed in terms of γ, r_B, δ_B and measured yields in CP-tagged D decays!

(Additional input comes from quantum correlated $K_s\pi\pi$ vs $K_s\pi\pi$ events)

Choice of bins informed by model, in order to maximise statistical sensitivity (only ~20% degradation w.r.t. unbinned fit)



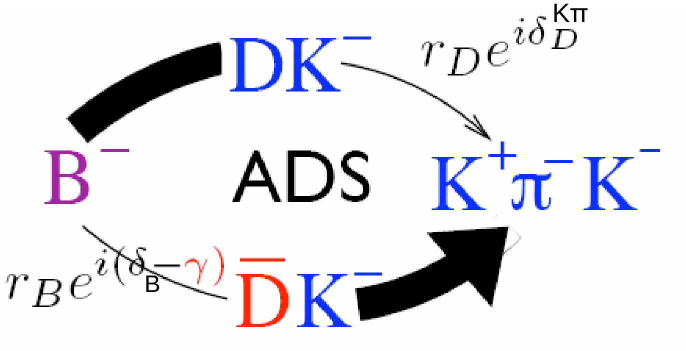
Bondar and Poluektov, arXiv:0801.0840

CLEO-c analysis in progress…

But no model error! Only residual uncertainty from finite CLEO-c statistics (~3^o)

Atwood-Dunietz-Soni (ADS) Method

Low interference scale of B→DK method (r_B~0.1) can be enhanced by exploiting Doubly Cabibbo Suppressed modes eg. $D^0 \rightarrow K^+\pi^-$



This introduces two new parameters:

$$\frac{< D^0 \longrightarrow K^+\pi^- >}{< \overline{D}^0 \longrightarrow K^+\pi^- >} = r_D^{K\pi} e^{i\delta_D^{K\pi}}$$

~0.06, ie. similar in magnitude to r_B

$r_D^{K\pi}$ known well, $\delta_D^{K\pi}$ unknown

4 possible final states, between 2 of which there can be a big CP-asymmetry:

$$\Gamma(B^- \rightarrow (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} - \gamma)$$
$$\Gamma(B^+ \rightarrow (K^-\pi^+)_D K^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} + \gamma)$$

these interference terms are 1st order

A powerful way to constrain γ, but need to know $\delta_D^{K\pi}$
Can be measured in quantum correlated D decays !

Measuring $\delta_D^{K\pi}$ in Quantum Correlated D Decays

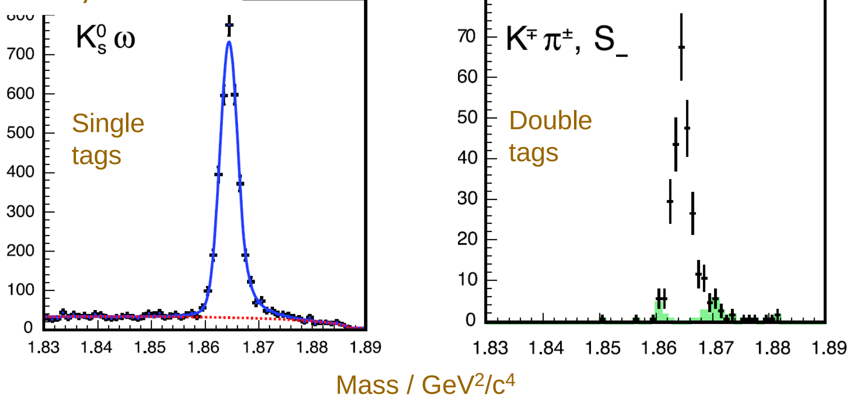
Idea: tag one D in CP eigenstate, other side is mixture of D^0 and $\bar{D}^0$, hence:

$$\text{Rate} \sim \ B_{CP+}\, B_{K\pi}\,(1 + \ 2 r_D^{K\pi} \cos \delta_D^{K\pi})$$

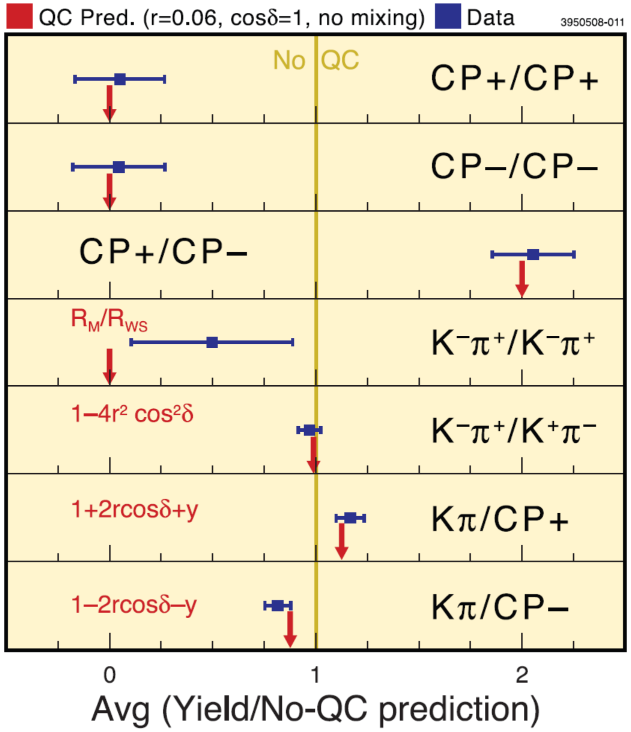
Approximate - full expression has additional dependence on mixing parameters x & y…

Analysis: measure set of single & double tag rates, with Kπ vs CP tags, & flavour tags

CLEO-c, 281 fb^{-1}



Extract $\delta_D^{K\pi}$, plus results on other parameters, including branching ratios.



CLEO-c: PRL 100 (2008) 221801; arXiv:0802.2268

Quantum correlations clearly seen !

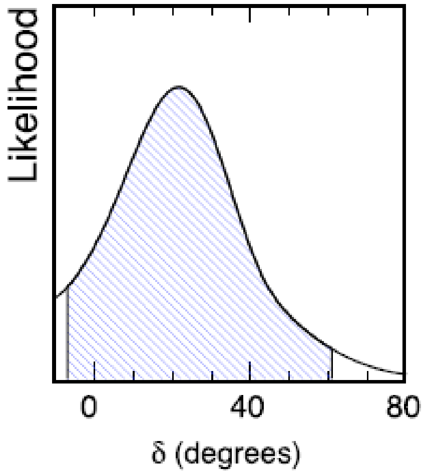
CLEO-c 281 fb^{-1} Results for $\delta_D^{K\pi}$

Result also important for charm mixing (x', y' measured in 'wrong sign' $K\pi$ analysis related to x, y through:

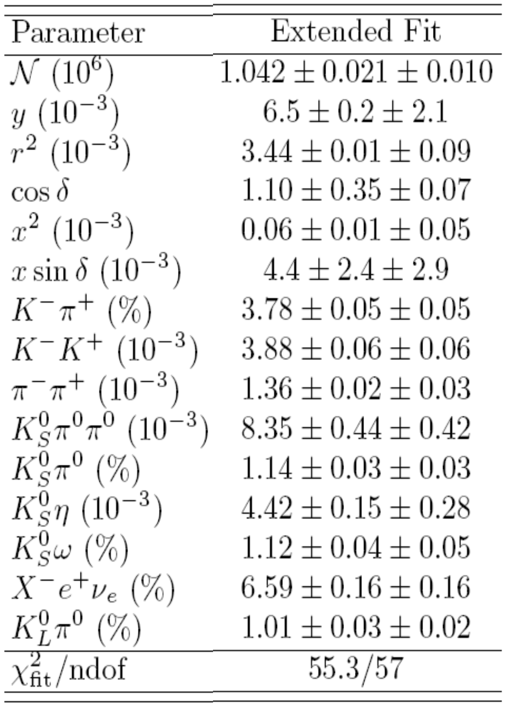
$$x' = x \cos \delta_D^{K\pi} + y \sin \delta_D^{K\pi}\ )$$

Most precise result on $\delta_D^{K\pi}$ obtained with mixing results used as external constraint:

$$\delta_D^{K\pi} = \left(22^{+11+9}_{-12-11}\right)^\circ$$



Fit results with all external constraints



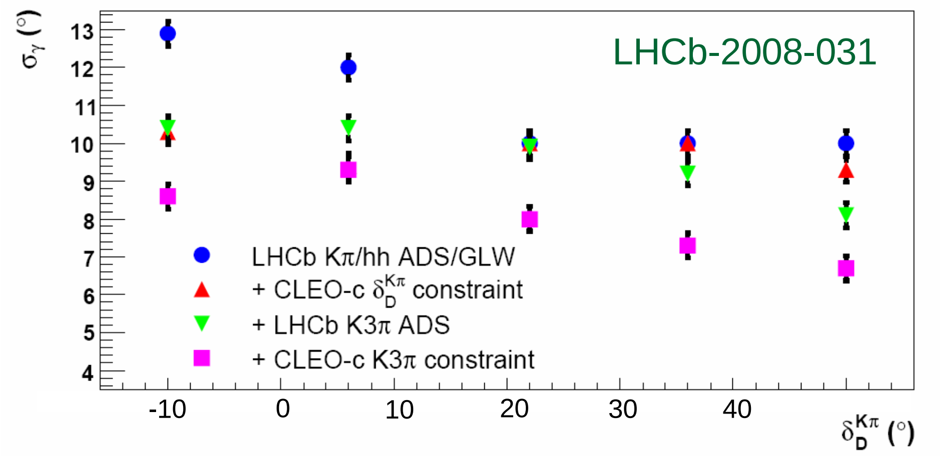
Parameter	Extended Fit
$\mathcal{N}$ (10^6)	$1.042 \pm 0.021 \pm 0.010$
y (10^{-3})	$6.5 \pm 0.2 \pm 2.1$
r^2 (10^{-3})	$3.44 \pm 0.01 \pm 0.09$
$\cos\delta$	$1.10 \pm 0.35 \pm 0.07$
x^2 (10^{-3})	$0.06 \pm 0.01 \pm 0.05$
$x \sin\delta$ (10^{-3})	$4.4 \pm 2.4 \pm 2.9$
$K^-\pi^+$ (%)	$3.78 \pm 0.05 \pm 0.05$
K^-K^+ (10^{-3})	$3.88 \pm 0.06 \pm 0.06$
$\pi^-\pi^+$ (10^{-3})	$1.36 \pm 0.02 \pm 0.03$
$K_S^0\pi^0\pi^0$ (10^{-3})	$8.35 \pm 0.44 \pm 0.42$
$K_S^0\pi^0$ (%)	$1.14 \pm 0.03 \pm 0.03$
$K_S^0\eta$ (10^{-3})	$4.42 \pm 0.15 \pm 0.28$
$K_S^0\omega$ (%)	$1.12 \pm 0.04 \pm 0.05$
$X^-e^+\nu_e$ (%)	$6.59 \pm 0.16 \pm 0.16$
$K_L^0\pi^0$ (%)	$1.01 \pm 0.03 \pm 0.02$
χ^2_{fit}/ndof	55.3/57

Result will improve with full 818 fb^{-1} data set, use of additional tags, and possible exploitation of 4170 MeV data.

Similar analysis can be done for $K\pi\pi\pi$ – but here need to worry about resonant substructure which brings dilution to ADS interference (see backup slides).

Expected Sensitivity to γ at LHCb

Expected γ precision with 2 fb^{-1} of data (one year) for ADS modes alone:



Improvements in going from 2-body ADS to 4-body ADS & adding constraints from CLEO-c

Add other measurements, especially $B \rightarrow D(K_S \pi^+ \pi^-)K$, & extrapolate to 10 fb^{-1}

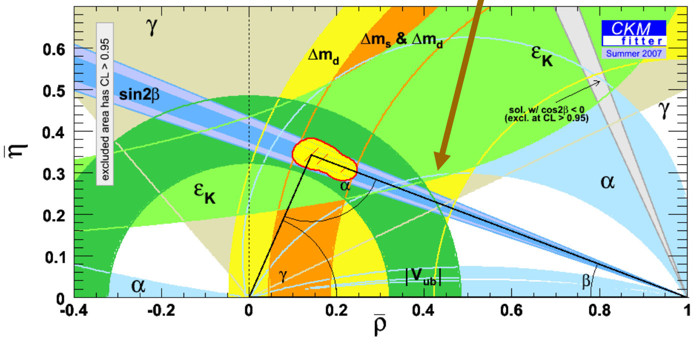
$\sigma_\gamma = 1.9 - 2.7^o$

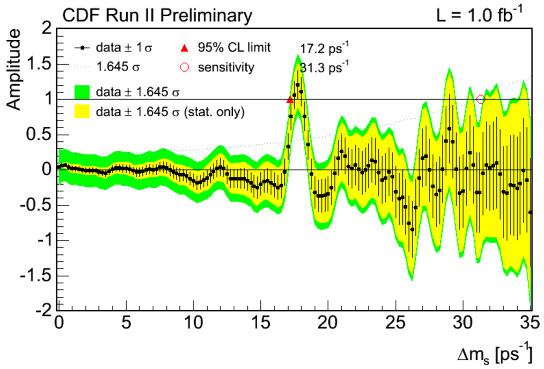
…in which B→DK methods have a weight of ~70%
(variation in number depends on values of phases)

Understanding of D decay properties central to precise measurement of γ !

Lattice QCD and the ‘Mixing Side’

‘Mixing side’ of unitarity triangle determined by B_d/B_s oscillation rates – box diagrams sensitive to new physics – and QCD corrections





Very well known (~0.3%), since observation of B_s mixing

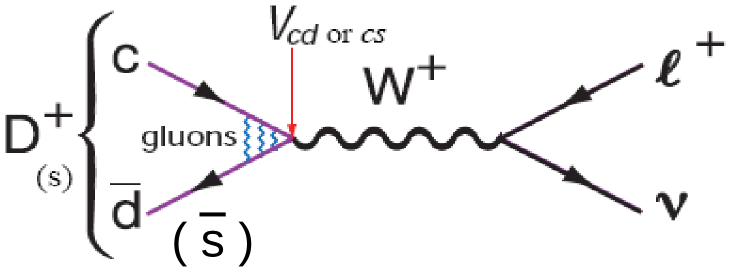
Length = $(f_{B_s}\sqrt{B_{B_s}}) / (f_{B_d}\sqrt{B_{B_d}})\ \sqrt{(\Delta m_d\, m_{B_d} / \Delta m_s\, m_{B_s})} = |V_{td}/V_{ts}|$

Calculated on lattice – present *assigned* uncertainty ~5% (and will decrease)

Highly desirable to cross-check lattice against experiment - go to D system !

Leptonic D Decays and Decay Constants

In D^+ and D_s c and spectator quark can annihilate to produce leptonic final state:



In general, for all pseudoscalars:

$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Since V_{cd} and V_{cs} well known, can extract f_D and f_{D_s} and compare with lattice !

Measurements of $D_{(s)}\to l\nu$ Branching Fractions

Precise measurements now exist for:

$\mu^+\nu$, $\tau^+ (\to\pi^+\nu)\upsilon$ CLEO-c (PRL 99 (2007) 071802; arXiv:0704.0437 + prelim)

D_s $\mu^+\nu$ BELLE (arXiv:0709.1340) & BaBar (hep-ex/0607094)

$\tau^+\to(e^+\nu\nu)\nu$ CLEO-c (PRL 100 (2008) 161801)

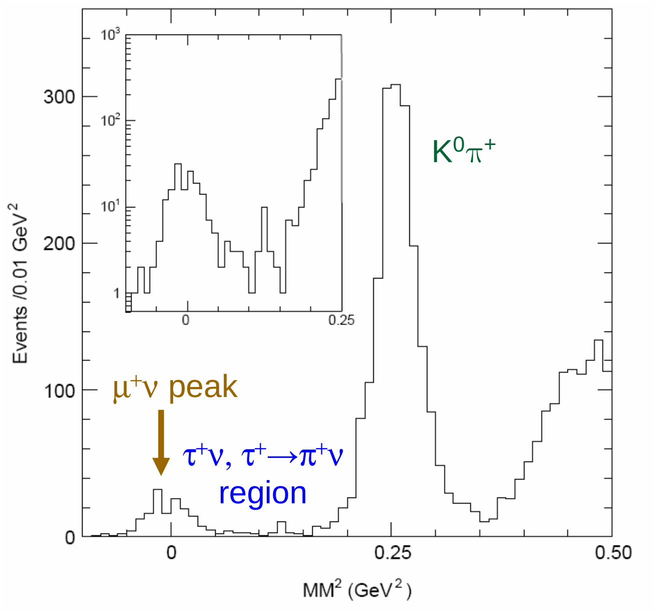
D^+ CLEO-c (arXiv:0806.2112)

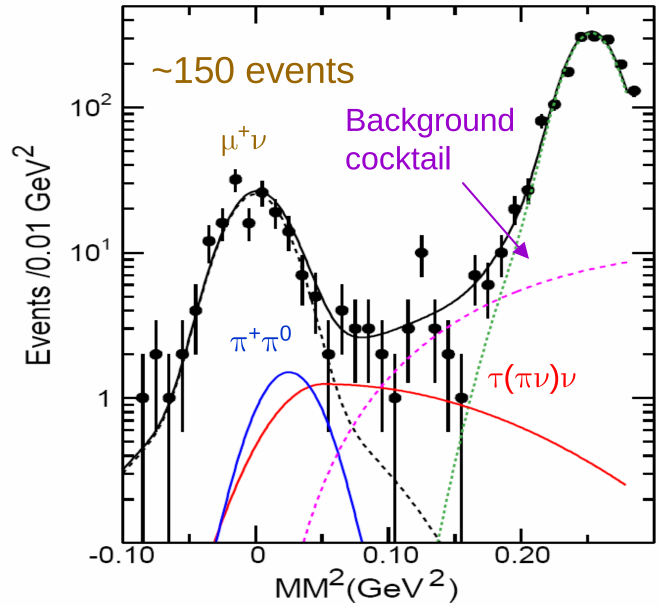
Basic method for $\mu\nu$ measurement:

- CLEO-c: for f_D reconstruct one D^+, look for MIP (μ), and then compute missing mass squared (similar for f_{D_s}, but here exploit $D_sD_s^*$ production in 4170 MeV dataset)
- B-factory: infer presence of D_s from recoiling mass against reconstructed D & fragmentation. Add candidate μ and compute missing mass

CLEO-c $D^+ \to \mu^+ \nu$

Missing mass squared distribution (incld. log zoom with fit):





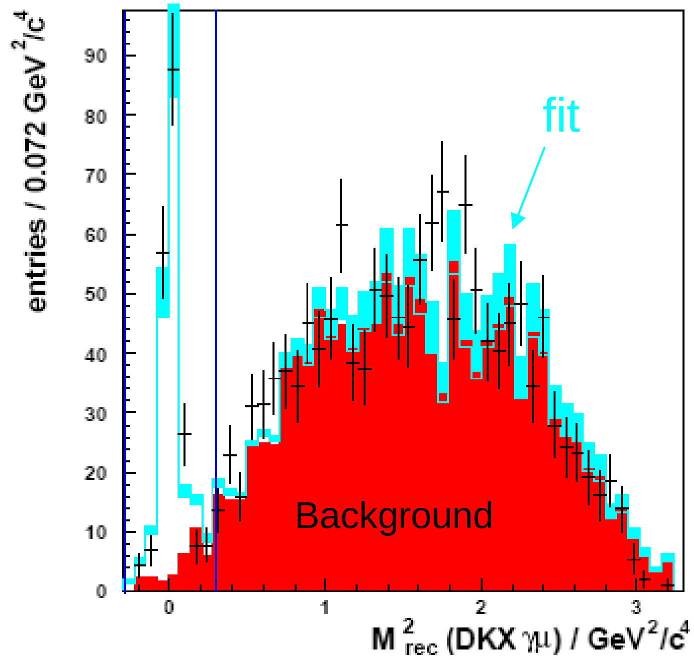
$$BR(D^+ \to \mu^+ \nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$$

$$f_D = (205.8 \pm 8.5 \pm 2.5)\ \text{MeV}$$

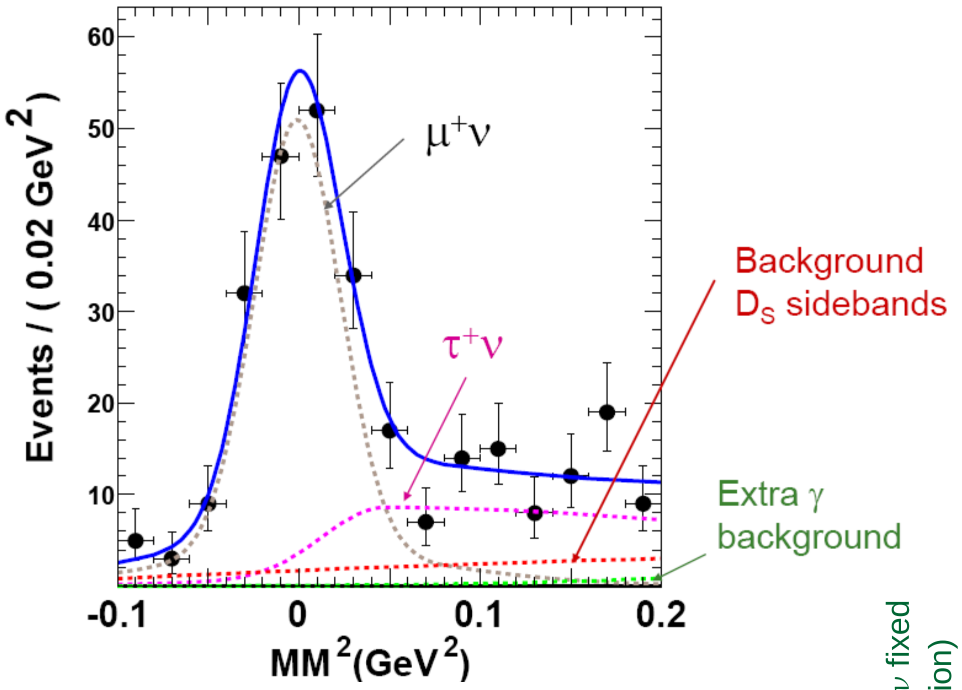
(result with $\tau\nu/\mu\nu$ fixed at SM expectation)

$D_s \to \mu^+ \nu$

Belle: 548 fb^{-1}



CLEO-c preliminary: 424 pb^{-1}



(result with $\tau\nu/\mu\nu$ fixed at SM expectation)

$BR(D_s \to \mu^+\nu) = (6.44 \pm 0.76 \pm 0.57) \times 10^{-3}$

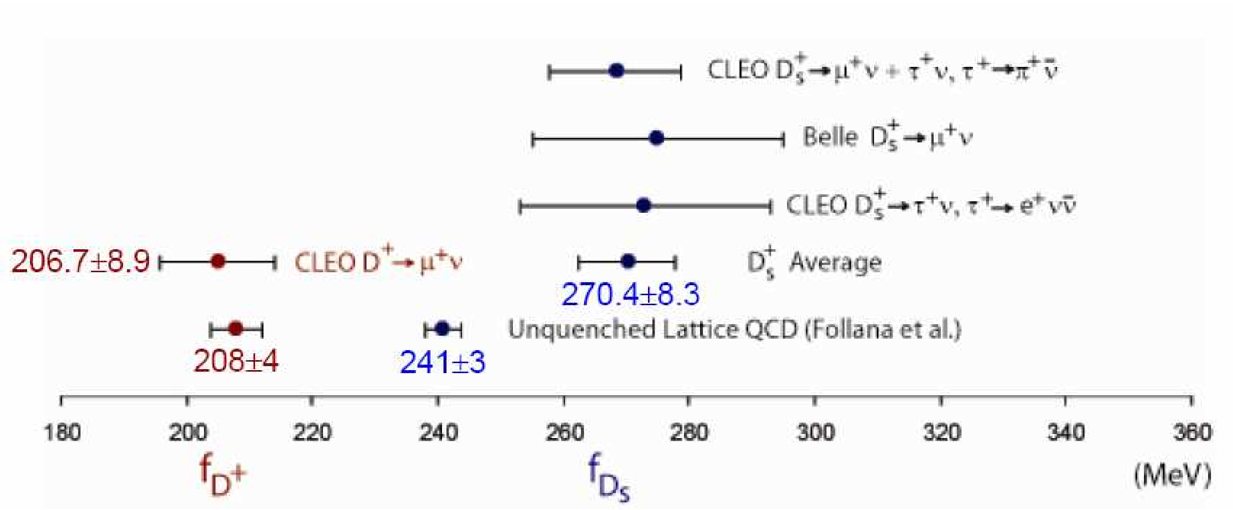
$f_{D_s} = (275 \pm 16 \pm 12)$ MeV

$BR(D_s \to \mu^+\nu) = (6.13 \pm 0.44 \pm 0.20) \times 10^{-3}$

$f_{D_s} = (268.2 \pm 9.6 \pm 4.4)$ MeV

D^+ and D_s Decay Constants: the Global Picture

f_D agrees well with lattice QCD; f_{D_s} measurements internally consistent, but more than 3.5 sigma away from lattice QCD !



Is there something wrong with calculation (implications for mixing side) or is it new physics (charged Higgs, leptoquarks… arXiv:0803.1898 ; arXiv:0803.0512)?

Final D_s results from CLEO-c expected soon with full data sample

New Physics Searches in the D system

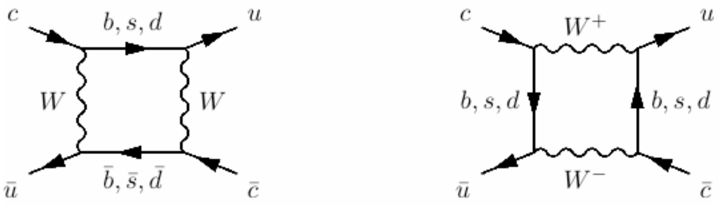
- D^0-$\overline{D}^0$ oscillations (in brief – see next talk)
- The search for CP violation
- Rare decays

D^0-$\bar{D}^0$ Mixing

D^0–$\bar{D}^0$ transitions have two observables:

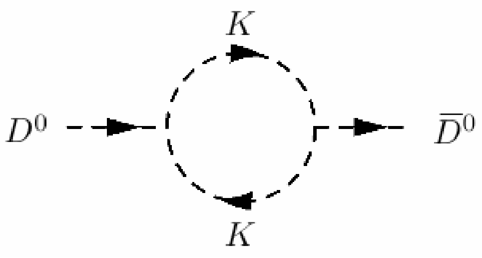
$$x = \frac{\Delta M}{\Gamma}, \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

Short-distance



Boxes and loops in charm transitions involve down-type quarks – this gives charm system unique new physics sensitivity.

Long-distance



SM calculations based on box diagrams alone gives $x \sim 10^{-5}$, $y \sim 10^{-7}$ [Falk et al. PRD 65 (2002) 054034]

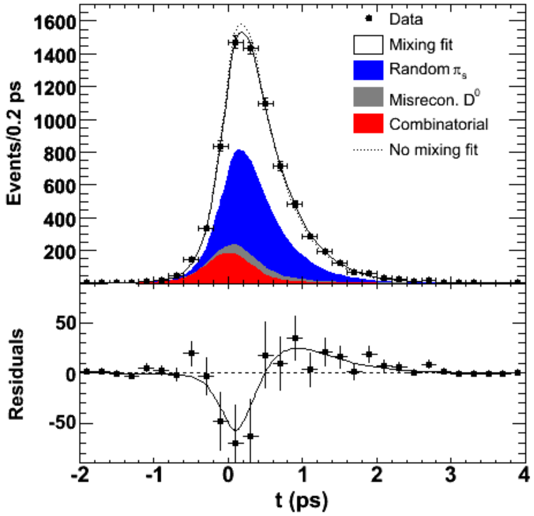
y should be dominated by long-distance effects, and is generally considered to be immune to NP (but not always, ie. [Petrov & Yegiyan PRD 77 (2008) 034018]). So x>>y would point to NP!

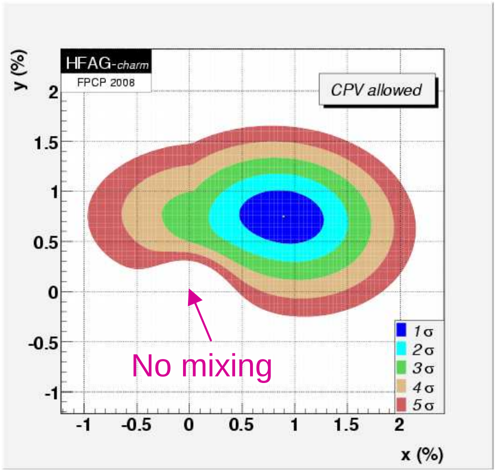
D^0-$\overline{D}^0$ Mixing: Observation

Numerous recent, exciting results on charm mixing (see Joerg Marks' talk).

The most interesting…

- 'Wrong sign' $K\pi$ (x'^2, y')
  - BELLE PRL 96 (2006) 151801
  - BaBar PRL 98 (2007) 211802
  - CDF PRL 100 (2008) 121802
- Eigenstate lifetime analyses: y_{CP}
  - BaBar arXiv:0712.2249
  - BELLE PRL 98 (2007) 211803
- $K_S\pi^+\pi^-$ Dalitz analyses: x,y
  - BELLE PRL 99 (2007) 131803





No doubt now that mixing has been seen…

$$x = 0.89\pm^{0.26}_{0.27}\ \%$$

$$y = 0.75\pm^{0.17}_{0.18}\ \%$$

(HFAG May 08,
CPV allowed)

…but what does it mean?

D^0-$\overline{D}^0$ Mixing: Interpretation

SM predictions for x & y have very large spread in value.

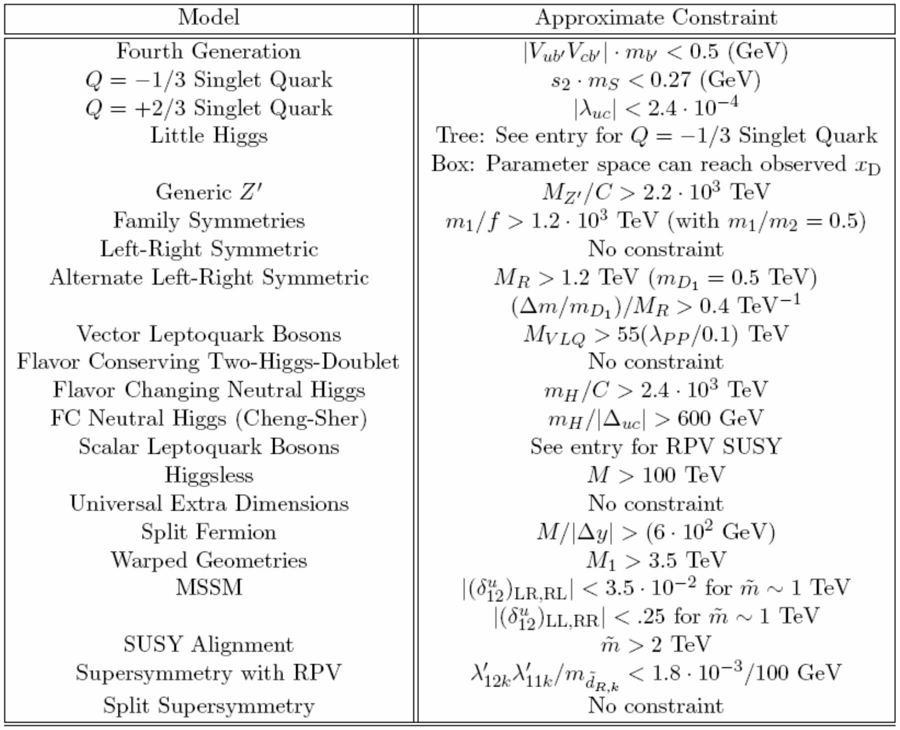
Observed values of parameters:

$x = 0.89 \pm^{0.26}_{0.27}$ %

$y = 0.75 \pm^{0.17}_{0.18}$ %

are on high side of what was expected, but are consistent.

Golowich, Hewett, Pakvasa and Petrov, PRL 98 (2007) 181801



Model	Approximate Constraint
Fourth Generation	$\lvert V_{ub'}V_{cb'}\rvert \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark	$\lvert\lambda_{uc}\rvert < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark Box: Parameter space can reach observed $x_{\rm D}$
Generic Z'	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
Left-Right Symmetric	No constraint
Alternate Left-Right Symmetric	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV) $(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet	No constraint
Flavor Changing Neutral Higgs	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher)	$m_H/\lvert\Delta_{uc}\rvert > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion	$M/\lvert\Delta y\rvert > (6 \cdot 10^2$ GeV$)$
Warped Geometries	$M_1 > 3.5$ TeV
MSSM	$\lvert(\delta^u_{12})_{\rm LR,RL}\rvert < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV $\lvert(\delta^u_{12})_{\rm LL,RR}\rvert < .25$ for $\tilde{m} \sim 1$ TeV
SUSY Alignment	$\tilde{m} > 2$ TeV
Supersymmetry with RPV	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

For this reason, and since x~y, no immediate sign of new physics, but plenty of useful constraints can be derived

CP Violation in the Charm System

If D mixing discovery has not (immediately) revealed New Physics, where to look?
Answer: CP violation ! Extremely small in SM (~ only 2 generations participate).

Two possible sources of CPV (there is another – see later):

ϕ - phase between mixing and decay

$(|q/p| -1)$ - where $D_{+,-} = p|D^0> \pm q|\bar{D}^0>$

both negligibly small in SM

So CP asymmetries possible in mixing (A^m) or between mixing and decay (A^i):

$$A^m \propto -y/2\ (|q/p| - |p/q|) \cos\phi$$

$$A^i \propto x/2\ (|q/p| + |p/q|) \sin\phi$$

New Physics observable giving non-0 ϕ or $(|q/p|-1)$ suppressed by x, $y \sim 10^{-2}$.
So if something is seen it will be very small – but not as small as once feared !

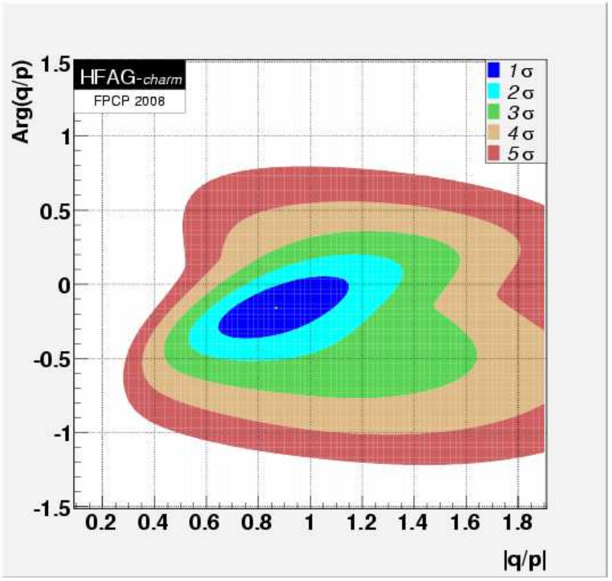
Indirect CP Violation in Charm: Status & Prospects

Generalising the mixing analyses to allow for CPV violation gives sensitivity to the two parameters governing CPV in mixing and mixing-decay interference.

So far no evidence of CPV, but existing limits are already quite impressive:

$$|q/p| = 0.87 \pm^{0.18}_{0.15}$$

$$\phi = -9.1 \pm^{8.1}_{7.8} \text{ degrees}$$



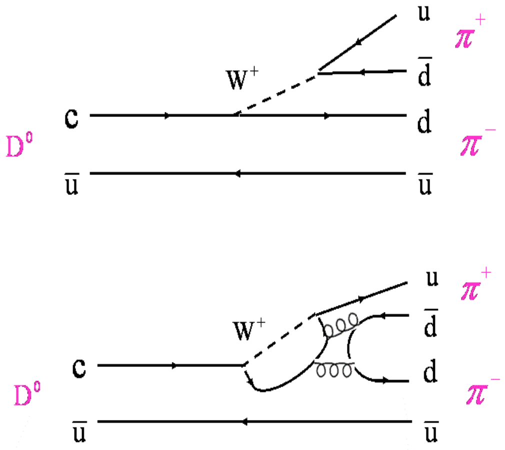
Higher sensitivity will come as mixing analyses improve precision – wait for LHCb (and beyond)

Many NP models expect effects here (eg. flavour alignment in SUSY)

CPV in Singly Cabibbo Suppressed D decays

Singly Cabibbo Suppressed (SCS) decays - a win-win scenario for CPV searches

Interference between tree and Penguin can generate both direct CP asymmetries which:



- Could reach ~10^{-3} in SM - may be observable!
- In many NP models effects of ~10^{-2} possible (see eg. Grossman, Kagan, Nir, PRD 75 (2007) 036008)

Task therefore is to look for CPV in SCS:

- Time integrated asymmetries in CP eigenstates, eg. KK, ππ (involves other types of CPV, not just direct)
- Asymmetries in charged D decays, eg. KKπ
- Asymmetries in final state distributions, eg. Dalitz plots and moments (may be most sensitive)

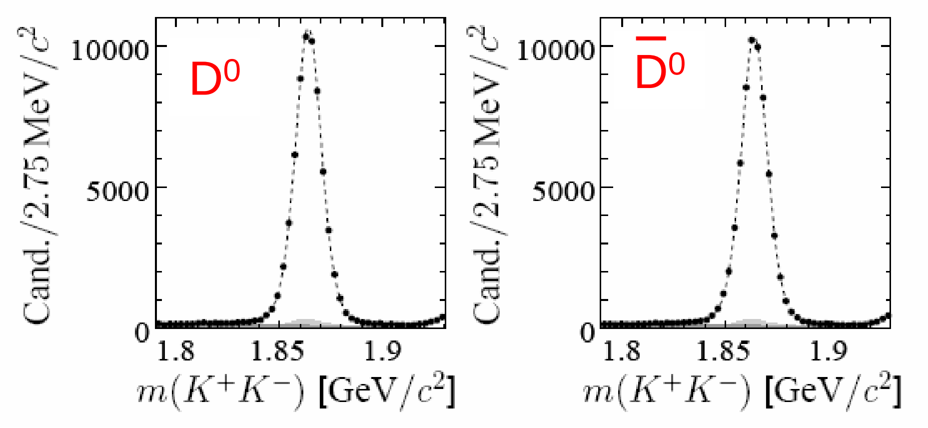
CPV searches in $D^0 \to KK, \pi\pi$

Measure asymmetry in time integrated rates:

$$A_{CP} = \frac{\Gamma(D^0 \to KK(\pi\pi)) - \Gamma(\overline{D}^0 \to KK(\pi\pi))}{\Gamma(D^0 \to KK(\pi\pi)) + \Gamma(\overline{D}^0 \to KK(\pi\pi))}$$

Distinguish D flavour from 'slow pion' charge in $D^* \to D^0\pi$

BaBar, PRD 100 (2008) 061803



386 fb^{-1} , ~130k KK events

Spot the difference….

Use $K\pi$ events to calibrate out asymmetries in slow π reconstruction. Form CP asymmetry in bins of θ to account for EW (γ-Z) FB asymmetries.

A_{CP} = 0.00 ± 0.34 (stat) ± 0.13 (syst)%

Entering interesting territory !

(dominates HFAG world average)

LHCb will accumulate > 50x statistics in this mode – big improvements possible…

CPV Searches in Multibody ($n \geq 3$) Decays

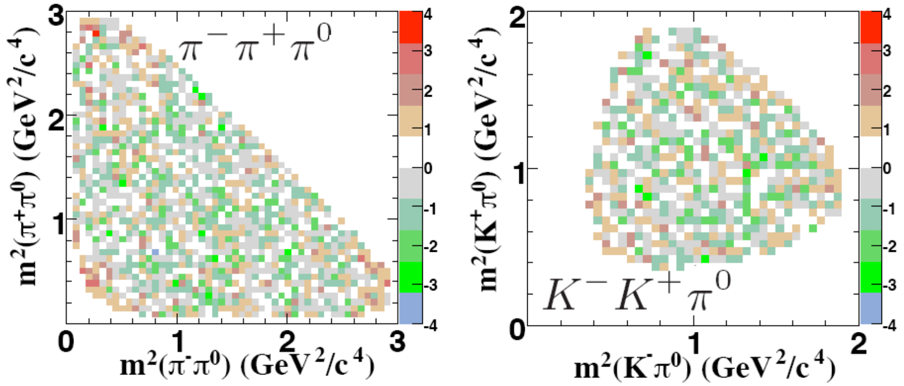
Final state distributions in 3 and 4-body decays allow for other strategies, some with higher sensitivity than simple comparisons of integrated rates.

eg. BaBar study of $K^+K^-\pi^0, \pi^+\pi^-\pi^0$

Several complementary analyses:

- Form residuals of D^0, $\bar{D}^0$ w.r.t. mean in Dalitz space
- Look for difference in angular moments of D^0 & $\bar{D}^0$ distributions
- Compare amplitude fits of D^0 & $\bar{D}^0$ Dalitz spaces (model dependent)
- Look for phase space integrated asymmetry.

385 fb^{-1}, arXiv:0802.4035



Consistent with no CPV at 33% and 17%

Other example: FOCUS T-odd moments study in $D \rightarrow KK\pi\pi$ (PLB 622 (2005) 622)

New Physics Searches with Rare D Decays

Example: $c \to u l^+ l^-$. Initially, exclusive modes look unpromising for NP searches, in contrast to B decays.

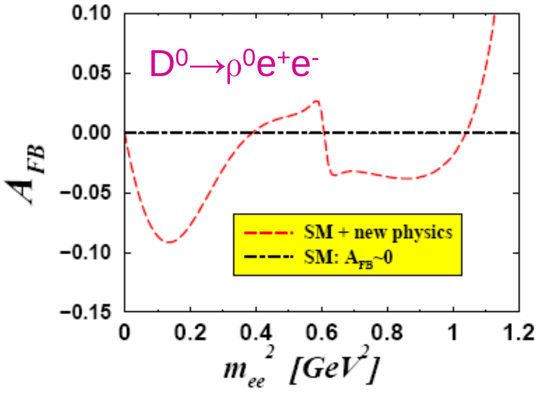
Why? Because short distance effects are swamped by long distance contributions.

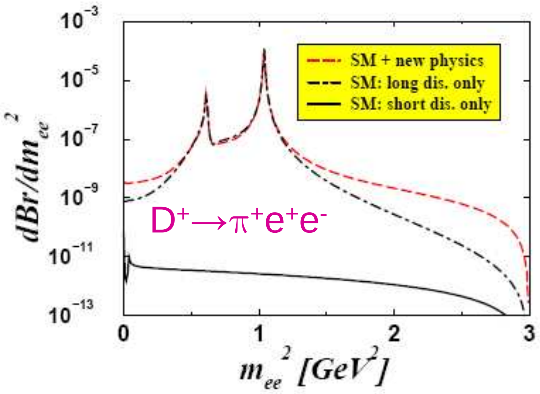
Br	short distance contribution only		total rate ≃ long distance contr.	experiment
	SM	SM + NP		
$D^+ \to \pi^+ e^+ e^-$	6×10^{-12}	8×10^{-9}	1.9×10^{-6}	$< 7.4 \times 10^{-6}$
$D^+ \to \pi^+ \mu^+ \mu^-$	6×10^{-12}	8×10^{-9}	1.9×10^{-6}	$< 8.8 \times 10^{-6}$
$D^0 \to \rho^0 e^+ e^-$	negligible	5×10^{-10}	1.6×10^{-7}	$< 1.0 \times 10^{-4}$
$D^0 \to \rho^0 \mu^+ \mu^-$	negligible	5×10^{-10}	1.5×10^{-7}	$< 2.2 \times 10^{-5}$

However, differential distributions, and FB asymmetries, still have discriminating power.

And total rate can still be sizably enhanced in some cases: $D^0 \to \mu\mu$ ~10^{-13} in SM, can go up to 10^{-7} in R-parity violating SUSY

NP models with extra up-type quark. From arXiv:0801.1833





Conclusions

Charm has stepped back into the front-line of flavour physics

- SM description of CP violation has withstood its first attack (from the B-factories and Tevatron). Next phase of measurements, at LHCb, will have heavy reliance on what we understand about D decays.

- The D meson system is an excellent place to look for new physics (and one which is complementary to the B sector). In particular the ~ zero expected CP violation in the SM gives a near background-free environment in which to search. The observation of D-mixing gives us heart.

So, as well as being instrumental in the establishment of the SM,
charm may yet play a role in its dethronement!